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DOI:

[10.1016/j.lwt.2017.03.012](https://doi.org/10.1016/j.lwt.2017.03.012)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Prosapio, V & Norton, I 2017, 'Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance', *LWT - Food Science and Technology*, vol. 80, pp. 401-408.
<https://doi.org/10.1016/j.lwt.2017.03.012>

[Link to publication on Research at Birmingham portal](#)

Publisher Rights Statement:

Published in LWT-Food Science and Technology
<https://doi.org/10.1016/j.lwt.2017.03.012>

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Influence of osmotic dehydration pre-treatment on oven drying and freeze drying performance

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Abstract

Drying is largely used in food industry, since it allows prolonging the product shelf life by inhibiting microorganisms' growth and enzyme activity. Traditional drying techniques, such as air drying and freeze drying, suffer from several drawbacks, mainly long processing time, low rehydration capacity and change in food properties. Some pre-treatments, such as osmotic dehydration, can be applied prior to conventional techniques in order to produce an intermediate moisture product and, therefore, to improve the drying process. In this work, the influence of osmotic dehydration on oven drying and freeze drying performance was evaluated. Firstly, the effects of the main osmotic dehydration parameters were investigated in order to find the best conditions for water desorption. Secondly, experiments with oven drying, freeze drying and their combination with osmotic pre-treatment were carried out. Results of each technique in terms of final moisture content, water activity, rehydration ability, textural properties and microstructure were compared and discussed. It has been observed that the application of the pre-treatment allows reducing considerably the processing time and better retaining the food properties.

Keywords: Food drying, Osmotic dehydration, Oven drying, Freeze drying, Rehydration.

1. Introduction

Food market increasingly requires the development of techniques able to extend foodstuffs shelf-life, since consumers demand fresh-quality products without the use of preservatives (Maskan, 2001).

Fruits and vegetables are highly perishable foods, since they easily undergo degradation reactions by bacteria proliferation, because of their elevated moisture content (Dev & Raghavan, 2012). For this reason, several industrial processes have been developed for their preservation. Among them drying is the most common method, since water removal inhibits microorganisms' growth and enzyme activity and decreases the weight of the product, simplifying also its transport and storage (de Bruijn et al., 2016). For these purposes, dried foods should have water content lower than 25 g/100 g and water activity lower than 0.6 (de Bruijn et al., 2016; Stevenson et al., 2015). Water activity (a_w) is a measure of the quantity of water that is available for chemical and biological reactions, so it represents an indication of food stability with respect to microbial growth (Oliveira, Brandão, & Silva, 2016). On the other hand, downstream the drying process, it should be possible to recover the properties of the fresh food rehydrating the dried. Rehydration ability depends on the degree of cellular and structural disruption; therefore, it is considered as a measure of the damage caused by drying to the food structure (Vega-Gálvez et al., 2015).

Different drying processes have been proposed in literature. The most popular and ancient dehydration technique is air drying, in which moisture is removed by evaporation (Ratti, 2001). However, several authors reported that this process can cause several adverse effects on food attributes such as case hardening, shrinkage, poor rehydration ability and the alteration of the sensory features (Maskan, 2000). Another common technique is

represented by freeze drying, which consists in the freezing of the product and then water removal by sublimation. This technique allows to retain food quality and structure better than other dehydration processes , but it suffers from some drawbacks, such as high energy costs and very long processing times, which restricts its applicability to high-value products (Karam, Petit, Zimmer, Baudelaire Djantou, & Scher, 2016).

In order to optimise moisture desorption, some pre-treatments have also been proposed, with the aim to produce an intermediate moisture product. Among them, osmotic dehydration has received much attention due to its low cost and complexity. This process consists of the immersion of the foodstuff in a hypertonic solution: in this way moisture diffuses from the food towards the solution thanks to the semi-permeability of the cell membrane and, in the opposite way, the solute used as osmotic dehydrator flows from the solution to the food, even if in minor extent (da Costa Ribeiro, Aguiar-Oliveira, & Maldonado, 2016). Different authors (Rastogi & Raghavarao, 1997; Tsotsas & Mujumdar, 2014) reported that this method allows reducing water content up to 50 % weight. In order to complete the drying, other methods, as those mentioned above, need then to be applied.

In literature many papers are focused on osmotic dehydration and its application prior to microwave drying (Botha, Oliveira, & Ahrné, 2012; Corrêa, Dev, Gariepy, & Raghavan, 2011; de Bruijn & Bórquez, 2014; Prothon et al., 2001), but limited studies have been performed till date on osmotic dehydration + oven drying and osmotic dehydration + freeze drying. In these studies, the authors focused their attention on water desorption, but rarely on the effects of drying on water activity, rehydration capacity and food microstructure in order to have a comprehensive overview of the process. De Costa Ribeiro et al. (da Costa Ribeiro et al., 2016) observed that when osmotic dehydration was applied prior to conventional oven drying, a reduction of 41.8 % of the drying time was possible to

achieve a pear final moisture-content of 0.25 kg/kg dry solids; however, they did not report the samples' final water activity and rehydration capacity. Patil et al. (Patil, Kalse, & Jain, 2012) also observed that the application of the pre-treatment to convective drying allowed to reduce onion drying time by approximately 40 % but the effect on samples' water activity and microstructure was omitted. Ruiz-López et al. (Ruiz-López, Huerta-Mora, Vivar-Vera, Martínez-Sánchez, & Herman-Lara, 2010) pointed out that the osmotic dehydration pre-treatment led to a significant decrease in chayote moisture content, allowing to reduce air-drying time up to 65 % depending on the used dehydrator; however, also in this case, information about water activity, rehydration ability and structural properties were missing.

In the present work, osmotic dehydration was applied prior to oven drying and freeze drying in order to improve their performances. The model food chosen for the experimentation was strawberry, since it is one of the most consumed fruits, thanks to its enjoyable organoleptic characteristics and its healthy properties. First, an optimisation of the pre-treatment operating conditions was carried out in order to identify the best conditions for the highest water desorption. Several experiments were then performed using oven drying, osmotic dehydration + oven drying, freeze drying and osmotic dehydration + freeze drying. The results in terms of samples' final moisture content, water activity, rehydration ability and quality retention were compared and discussed.

2. Materials and methods

2.1 Materials

Fructose (purity ≥ 99 %), Maltodextrin (purity ≥ 99.5 %), Maltose (purity ≥ 95 %) and Sucrose (purity ≥ 99.5 %) were supplied by Sigma Aldrich (UK). All materials were used as received. Fresh strawberries (*Malling centenary*) were purchased by a local supermarket

and stored in a refrigerator at 5 °C. After washing in tap water and draining with blotting paper, strawberries were cut into cubes of 1 cm³.

2.2 Osmotic dehydration

Osmotic dehydration experiments were carried out by immersion of 10 g of strawberry cubes in the osmotic solution, at fixed temperature, under stirring at 250 rpm. The fruit to solution ratio (F:OS) was fixed at 1:10. At the end of each experiment, samples were taken and blotted with paper.

2.3 Oven drying

Conventional drying tests were carried out introducing strawberry cubes in an oven (Fistreem International Co. Ltd, Leicestershire, UK) with no flow air, at room pressure and fixed temperature.

2.4 Freeze drying

Fresh cubic samples were frozen at -20 °C and then lyophilised using a bench top Freeze Dryer (SCANVAC Coolsafe™, model 110-4, Lynge, Denmark), condenser temperature -110 °C, pressure 10 Pa.

2.5 Moisture content analysis

Moisture content (MC) analyses were carried out using a moisture analyser (model MB 25, OHAUS, Nanikon, Switzerland). Two grams of sample were placed within the aluminium pans and located over the pan support of moisture meter. Halogen element inside the moisture meter provides uniform infrared heating. It heats the sample at a set

temperature of 120 °C until the sample weight becomes constant. Moisture percentage as a function of weight change is recorded and displayed. Strawberry initial moisture content was found to be equal to 86.4 g/100 g.

2.6 Water activity analysis

Water activity (a_w) of fresh and dried samples was measured using an AquaLab® dew point water activity meter (model 4TE, Decagon Devices Inc., Pullman, WA, USA). The temperature controlled sample chamber was set to 25 °C. The water activity of the fresh samples was found to be equal to 0.988.

2.7 Soluble solids gain determination

Total solids content (SS) was determined by direct reading using an automatic refractometer (Model J357, Rudolph Research Analytical, Hackettstown, NJ, USA). The solids gain (SG %) was calculated using the following equation (Campos, Sato, Tonon, Hubinger, & Cunha, 2012):

$$SG \% = \frac{(SS_f \cdot w_f - SS_0 \cdot w_0)}{w_0}$$

Where: SS_f is the soluble solid content (° Bx) after osmotic dehydration; w_f is the sample weight after osmotic dehydration (g); SS_0 is the initial soluble solid content (° Bx); w_0 is the sample initial weight (g). Strawberry initial solid content (SS_0) in 10 g (w_0) of fruits was found to be equal to 2.05 ° Bx.

2.8 Rehydration

Rehydration experiments were performed by immersing a weighed amount of dried samples into distilled water at room temperature. The samples were removed at regular intervals, blotted with paper to eliminate the surface water and then reweighed.

Rehydration capacity (RC) was measured for all the samples using the following equation (de Bruijn & Bórquez, 2014):

$$RC = \frac{(w(t) - w_d)}{(w_0 - w_d)} 100$$

Where: $w(t)$ is the sample weight at time t (g) and w_d is the dried sample weight (g). Then, the rehydration behaviour was determined plotting RC as a function of the time.

2.9 Texture analysis

A texture analyser (TA.XT plus, Stable Micro System Ltd, Surrey, UK) with a cylinder probe (2 mm diameter) was used for puncture penetration test analysis. The probe was used to measure the maximum force required to penetrate an individual rehydrated piece of strawberry, to a depth of 2 mm, positioned horizontally over a heavy duty platform. The speed of approach of the probe was 2 mm/s and a 5 kg load cell was used. For each experiment the mean maximum penetration force (N) was recorded.

2.10 Confocal scanning laser microscopy

The microstructure of the strawberry samples was visualised at room temperature using a confocal scanning laser microscope (Leica TCS SPE, Heidelberg, Germany) equipped with laser operating at a wavelength of 532 nm. To study how the strawberry structure is affected by drying, samples were first rehydrated and then a cross section with a thickness

equal to 1 mm was cut for observation with the microscope. Before imaging, samples slices were stained with Nile red solution and covered with a cover slip.

2.11 Statistical analysis

All measurements were performed in triplicate and are reported as mean and standard deviation. Data were analysed by one-way analysis of variance (ANOVA) and Tukey's multiple comparison tests, using SigmaPlot 12.5 Statistical Software. The level of significance was defined as $p \leq 0.05$.

3. Results and discussion

In the first part of the experimentation, an optimisation of the osmotic dehydration operating parameters was carried out in order to identify the conditions that assure the highest water desorption. Afterwards, experiments were performed with oven drying, freeze drying and their combination with osmotic dehydration, in order to verify the effectiveness of the pre-treatment.

3.1 Osmotic dehydration

Osmotic dehydration experiments were carried out investigating the following effects: type of osmotic agent, concentration of the osmotic solution, temperature and processing time. In Table 1, a list of the experiments is reported with the indication of the operating conditions employed, the percentage of moisture content in the pre-treated samples, their water activity and solid gain .

3.1.1 *Effect of the type of osmotic agent*

The first set of experiments was performed at 25 °C, with a fruit to solution ratio (F:OS) equal to 1:10, a processing time equal to 3 h and a concentration of 40 °Bx, varying the kind of osmotic agent, since it has been observed to have a major influence on the mass transfer rate (Atarés, Chiralt, & González-Martínez, 2008). Dehydrators must be effective, convenient, non-toxic, with a good taste and should not react with the product (Yadav & Singh, 2014). In this work, Fructose, Maltose, Sucrose and Maltodextrin were tested as osmotic agents (runs #1-4 in Table 1) in order to investigate which one lead to a more efficient dehydration.

Comparing the data obtained from these experiments, it was observed that when Fructose was used as osmotic agent, samples showed the lowest moisture content (58.9 g/100 g) and water activity (0.951), as reported in Table 1. Therefore, this osmotic agent was chosen for the further experiments.

According to Panagiotou et al. (Panagiotou, Karathanos, & Maroulis, 1999), during osmotic dehydration low molecular weight solutes lead to higher water loss and higher solid uptake than high molecular weight solutes. Our results confirmed their observation since, among the investigated sugars, Fructose has the lowest molecular weight (as shown in Table 2) and the soluble solid content, that in the fresh strawberry was equal to 2 °Bx, was increased up to 2.15 % in the samples osmotically treated with this sugar (run #4 in Table 1).

3.1.2 *Effect of the osmotic solution concentration*

The second effect taken into account was the concentration of the osmotic solution, which was varied from 20 to 60 °Bx and compared to 40 °Bx discussed above, keeping constant all the other parameters (runs #5-6 in Table 1). From the comparison of the

obtained results, it was possible to observe that increasing the concentration at 60 °Bx, i.e. increasing the dehydration driving force, the sample solid gain increased up to 3.2 % whereas the moisture content and the water activity significantly decreased. For this reason, it was decided to continue the experimentation fixing the concentration of the osmotic solution at 60 °Bx.

3.1.3 Effect of the operating temperature

The influence of the operating temperature on the osmotic dehydration process was investigated using 35 and 50 °C (runs #7-8 in Table 1). From these experiments, it has been observed that increasing the temperature the dehydration efficiency increased, reaching a moisture content equal to 18.77 g/100 g and a water activity equal to 0.705 at 50 °C and 3 h processing. This result is due to an increase of the cell membrane permeability and a reduction of the osmotic solution viscosity at higher temperature, which cause a decrease in the resistance to mass transfer (de Oliveira, Corrêa, de Angelis Pereira, de Lemos Souza Ramos, & Vilela, 2016). As a consequence, the solid gain also increased since there is a larger amount of sugar that flows from the solution towards the sample.

3.1.4 Effect of the processing time

During osmotic dehydration, water diffusion rate from the product is fast in the first few hours, thereafter it gradually decrease until the achievement of a plateau value; at the same time, when moisture loss lowers, the solute intake rate towards the product increases (Ahmed, Qazi, & Jamal, 2016). Therefore, it is very important to identify the appropriate processing time in order to find a good compromise between water desorption and solid uptake.

The influence of the processing time was studied performing experiments at 1 and 5 h (runs #9 and #10, respectively). Using a processing time of 1 h, the final moisture content was 3.5 times larger than the MC obtained at 3 h (run #8), as reported in Table 1. On the other hand, the use of a processing time equal to 5 h led to a higher water desorption; however, from a technological point of view, the improvement is not as significant as to justify the employment of such a long process. Moreover, the solid gain measured at this condition was much higher than that of run #8.

On the ground of the optimisation of the process parameters, the chosen conditions for the further dehydration experiments were those of run #8, i.e. Fructose as osmotic agent, temperature of 50 °C, concentration equal to 60 °Bx and processing time equal to 3 h.

3.2 Oven drying

Conventional drying tests were carried out studying the effects of the operating temperature and the processing time.

3.2.1 Effect of the operating temperature

In a first step, experiments were performed with a processing time equal to 5 h, at different operating temperatures, in order to determine the best condition for drying. In Table 3, a list of the experiments with the corresponding conditions and results is reported.

When the oven temperature was fixed at 40 °C (run #1 in Table 3), it was observed only a slight reduction of the sample moisture content and the water activity compared to the fresh sample. At 50 °C (run #2 in Table 3), a further improvement of the results was observed. At 60 °C (run #3 in Table 3), the reduction of the moisture content was more evident but the samples, from a macroscopic point of view, appeared partially melted.

However, in all the cases, the samples' water activity was still high; therefore, longer processing times might be required to achieve the threshold value to avoid microbial proliferation (Stevenson et al., 2015).

3.2.2 Effect of the processing time

In order to identify the processing time needed to obtain a MC lower than 20 g/100 g, the evolution of the moisture content was monitored as function of the time at 50 °C, as shown in Fig. 1.

As shown in Fig. 1, about 8 h of processing are needed to achieve a MC equal to 13 g/100 g. However, after 6 h the samples' structure was completely destroyed with a complete change in their shape and texture.

On the basis of these results, it is possible to conclude that oven drying cannot be considered an effective drying technique for strawberry processing. In order to improve the performance of this process, the osmotic dehydration pre-treatment was then applied.

3.2.3 Osmotic dehydration+ Oven drying

The best conditions identified from osmotic dehydration experiments (run #8 in Table 1) were fixed for the pre-treatment; samples were then processed using oven drying at 50 °C over a period of 2 h (run #4 in Table 3). At the end of the experiment, the moisture content was significantly reduced to 6.7 g/100 g and the water activity was reduced to 0.437; both the values were below the required threshold to avoid microbial spoilage.

Comparing this result with that of run #2 (Table 3), it is possible to deduce that using the same processing time (5 h), the combination of the two techniques provided a more efficient result with respect to the only oven drying.

3.3 Freeze drying

Freeze drying experiments were performed at different processing time, as shown in Fig. 2a and 2b, where the final moisture content and the water activity were plotted as a function of the time. From these diagrams, it can be seen that presumably at least 15 h are necessary to reach acceptable values from a microbiological point of view. In order to reduce the processing time, the combination osmotic dehydration + freeze drying was investigated.

3.3.1 Osmotic dehydration + freeze drying

For the osmotic dehydration the conditions of run #8 in Table 1 were chosen as the pre-treatment. For freeze drying, two processing times were investigated, as shown in Table 4 (runs #3-4).

Fixing the freeze drying processing time at 4 h (run #3 in Table 4), the moisture content reduced slightly with respect to the only osmotic dehydration (run #8 in Table 1), but the water activity value reduced significantly. Comparing this result with those obtained with the only freeze drying, it can be observed that the combination of the two techniques allows the total processing time to be reduced from 15 h to 7 h.

Increasing the freeze drying processing time to 7 h (run #4 in Table 4), showed a large reduction of the MC and a_w . This result, obtained with a total processing time of 10 h, can be reached in 18 h using the only freeze drying (run #2 in Table 4). Therefore, osmotic pre-treatment has been shown to be an effective way to significantly reduce the processing time and, as a consequence, the related energetic costs.

305

306 3.4 Rehydration behaviour

307 As already discussed in the *Introduction*, rehydration is a fundamental aspect in
308 drying process. In this phenomenon different physical mechanisms are involved: absorption
309 of water into the dried product, diffusion of water molecules through the porous network
310 and swelling (Ratti, 2008). The degree of rehydration is mainly influenced by the employed
311 drying process since it affects the integrity of the food structure.

312

313 3.4.1 Oven drying

314 In Fig. 3, the comparison between the rehydration behaviour of the oven drying and
315 osmotic dehydration+ oven dried samples is reported. When rehydrated, osmotic dried
316 samples reached a RC equal to 15.9 g/100 g; whereas osmotic dehydration+ oven dried
317 samples showed a relevant improvement of the rehydration capacity, achieving a value
318 equal to 30.7 g/100 g. This is a further evidence of the effectiveness of the osmotic pre-
319 treatment when applied to oven drying.

320

321

322 3.4.2 Freeze drying

323 In Fig. 4, a comparison between the rehydration behaviour of the freeze dried and
324 the osmotic dehydration + freeze dried samples is reported.

325 From these rehydration tests it is possible to observe that freeze dried samples
326 reached a rehydration capacity around 42 g/100 g, whereas pre-treated samples reached a
327 lower RC, equal to 30 g/100 g. This experimental evidence was already observed by some

authors (Ciurzyńska & Lenart, 2012; Seguí, Fito, & Fito, 2013); it could be due to the sample's shrinkage that occurs during the treatment which makes water absorption more difficult and slow.

In this case the pre-treatment had a detrimental effect on samples' rehydration ability when applied to freeze drying. However, these dried products could be used in applications in which rehydration is not necessarily required such as snacks and cereal mix.

3.5 Texture analyses

Texture is one of the most important quality criteria for food acceptability by consumers, especially for dried products. In this work, puncture penetration test was used as an indicator of strawberry textural properties; the analyses were carried out on fresh and rehydrated samples. The results of the tests in terms of maximum penetration force for each drying technique are shown in Fig. 5. The analyses revealed that drying process caused a decrease in strawberry firmness, independently from the used technique. Comparing the results of the different methods, it was found that textural properties were better retained when osmotic pre-treatment was applied. Texture is less preserved in oven dried samples since this technique caused a collapse of the microstructure with consequent softening of the macrostructure. Freeze dried samples, instead, showed intermediate results between pre-treated and oven dried samples.

3.6 Microstructure analyses

Strawberry has a complex internal structure, formed by many tissues which have different chemical composition and microstructure. The skeleton of this fruit is composed by the vascular tissue which is composed of long fibre and pith. The outer layer is formed by

epidermal cells; the inner layer is formed by hypodermal cells and cortical cells (Polito, Larson, & Pinney, 2002). In each cell it is possible to identify the intercellular volume, which contains vacuole and cytoplasm, and the extracellular volume, which comprises the cell membrane and the space between different cells. In order to localize cell membranes, samples were stained with Neil Red since it has the ability to bind to its phospholipids (Fujimura et al., 2007). Fig. 6 shows the cortex cells in fresh and rehydrated strawberries observed with the confocal scanning laser microscope.

As observed in Fig. 6a, unprocessed strawberry cells are 100's of μm and close to each other. In freeze dried and osmotic dehydration + freeze dried samples, shown in Fig. 6b and 6c respectively, the cells are still clearly visible which means that the processing did not affect the sample microstructure; moreover, in both the cases, they are smaller probably because samples were not able to reach the complete rehydration in the time of the study, as it was previously discussed. In the case of oven dried sample (Fig. 6d) it was not possible to identify cells since the sample microstructure was completely destroyed. When osmotic dehydration is applied prior to oven drying, the collapse of the structure is partially limited and some cells are still present even if broken in some points; this result explains why in these samples rehydration is higher than that of the oven dried samples.

4. Conclusions

In this work the influence of osmotic dehydration on oven and freeze drying performance has been carried out. It has been demonstrated that the application of the pre-treatment allows: a significant reduction the processing time and a better retention of the mechanical and structural properties of strawberry; to improve the rehydration ability in the case of oven dried samples.

375 These results can be relevant from an industrial point of view since they allow a better
376 understanding of the physical processes and could lead to a reduction in cost and
377 improvement in the quality of the product.

References

- Ahmed, I., Qazi, I. M., & Jamal, S. (2016). Developments in osmotic dehydration technique for the preservation of fruits and vegetables. *Innovative Food Science & Emerging Technologies*, 34, 29-43.
- Atarés, L., Chiralt, A., & González-Martínez, C. (2008). Effect of solute on osmotic dehydration and rehydration of vacuum impregnated apple cylinders (cv. Granny Smith). *Journal of Food Engineering*, 89, 49-56.
- Botha, G. E., Oliveira, J. C., & Ahrné, L. (2012). Quality optimisation of combined osmotic dehydration and microwave assisted air drying of pineapple using constant power emission. *Food and Bioproducts Processing*, 90, 171-179.
- Campos, C. D. M., Sato, A. C. K., Tonon, R. V., Hubinger, M. D., & Cunha, R. L. d. (2012). Effect of process variables on the osmotic dehydration of star-fruit slices. *Food Science and Technology (Campinas)*, 32, 357-365.
- Ciurzyńska, A., & Lenart, A. (2012). Erratum: Rehydration and sorption properties of osmotically pretreated freeze-dried strawberries (Journal of Food Engineering). [Erratum]. *Journal of Food Engineering*, 113, 361.
- Corrêa, J. L. G., Dev, S. R. S., Gariepy, Y., & Raghavan, G. S. V. (2011). Drying of pineapple by microwave-vacuum with osmotic pretreatment. *Drying Technology*, 29, 1556-1561.
- da Costa Ribeiro, A. S., Aguiar-Oliveira, E., & Maldonado, R. R. (2016). Optimization of osmotic dehydration of pear followed by conventional drying and their sensory quality. *LWT - Food Science and Technology*, 72, 407-415.
- de Bruijn, J., & Bórquez, R. (2014). Quality retention in strawberries dried by emerging dehydration methods. *Food Research International*, 63, Part A, 42-48.
- de Bruijn, J., Rivas, F., Rodriguez, Y., Loyola, C., Flores, A., Melin, P., & Borquez, R. (2016). Effect of vacuum microwave drying on the quality and storage stability of strawberries. *Journal of Food Processing and Preservation*, 40, 1104-1115.

404 de Oliveira, L. F., Corrêa, J. L. G., de Angelis Pereira, M. C., de Lemos Souza Ramos, A., & Vilela, M. B.
 405 (2016). Osmotic dehydration of yacon (*smallanthus sonchifolius*): optimization for fructan
 406 retention. *LWT - Food Science and Technology*, 71, 77-87.

407 Dev, S. R. S., & Raghavan, V. G. S. (2012). Advancements in drying techniques for food, fiber, and
 408 fuel. *Drying Technology*, 30, 1147-1159.

409 Fujimura, H., Dekura, E., Kurabe, M., Shimazu, N., Koitabashi, M., & Toriumi, W. (2007). Cell-based
 410 fluorescence assay for evaluation of new-drugs potential for phospholipidosis in an early
 411 stage of drug development. *Experimental and Toxicologic Pathology*, 58, 375-382.

412 Karam, M. C., Petit, J., Zimmer, D., Baudelaire Djantou, E., & Scher, J. (2016). Effects of drying and
 413 grinding in production of fruit and vegetable powders: a review. *Journal of Food Engineering*,
 414 188, 32-49.

415 Maskan, M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food*
 416 *Engineering*, 44, 71-78.

417 Maskan, M. (2001). Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and
 418 microwave drying. *Journal of Food Engineering*, 48, 177-182.

419 Oliveira, S. M., Brandão, T. R. S., & Silva, C. L. M. (2016). Influence of drying processes and
 420 pretreatments on nutritional and bioactive characteristics of dried vegetables: a review.
 421 *Food Engineering Reviews*, 8, 134-163.

422 Panagiotou, N. M., Karathanos, V. T., & Maroulis, Z. B. (1999). Effect of osmotic agent on osmotic
 423 dehydration fruits. *Drying Technology*, 17, 175-189.

424 Patil, M. M., Kalse, S. B., & Jain, S. K. (2012). Osmo-convective drying of onion slices *Research Journal*
 425 *of Recent Sciences*, 1, 51-59.

426 Polito, V. S., Larson, K. D., & Pinney, K. (2002). Anatomical and histochemical factors associated with
 427 bronzing development in strawberry fruit. *Journal of the American Society for Horticultural*
 428 *Science*, 127, 355-357.

429 Prothon, F., Ahrné, L. I. M., Funebo, T., Kidman, S., Langton, M., & Sjöholm, I. (2001). Effects of
 430 combined osmotic and microwave dehydration of apple on texture, microstructure and
 431 rehydration characteristics. *LWT - Food Science and Technology*, 34, 95-101.

432 Rastogi, N. K., & Raghavarao, K. S. M. S. (1997). Water and solute diffusion coefficients of carrot as a
 433 function of temperature and concentration during osmotic dehydration. *Journal of Food*
 434 *Engineering*, 34, 429-440.

435 Ratti, C. (2001). Hot air and freeze-drying of high-value foods: A review. *Journal of Food Engineering*,
 436 49, 311-319.

437 Ratti, C. (2008). *Advances in food dehydration*: CRC Press.

438 Ruiz-López, I. I., Huerta-Mora, I. R., Vivar-Vera, M. A., Martínez-Sánchez, C. E., & Herman-Lara, E.
 439 (2010). Effect of osmotic dehydration on air-drying characteristics of chayote. *Drying*
 440 *Technology*, 28, 1201-1212.

441 Seguí, L., Fito, P. J., & Fito, P. (2013). A study on the rehydration ability of isolated apple cells after
 442 osmotic dehydration treatments. *Journal of Food Engineering*, 115, 145-153.

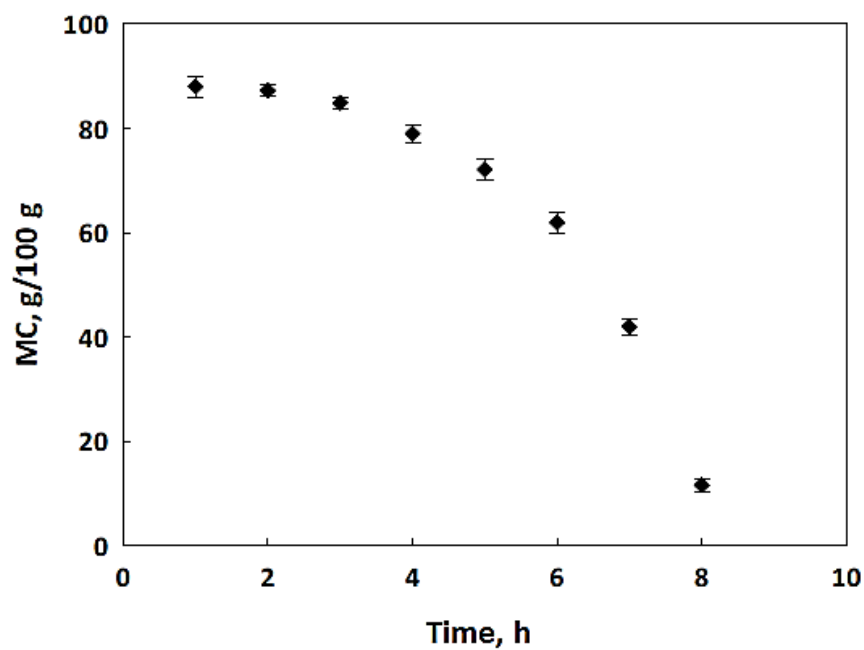
443 Stevenson, A., Cray, J. A., Williams, J. P., Santos, R., Sahay, R., Neuenkirchen, N., . . . Hallsworth, J. E.
 444 (2015). Is there a common water-activity limit for the three domains of life? *The ISME*
 445 *Journal*, 9, 1333-1351.

446 Tsotsas, E., & Mujumdar, A. S. (2014). *Modern Drying Technology* (Vol. 1-4).

447 Vega-Gálvez, A., Zura-Bravo, L., Lemus-Mondaca, R., Martinez-Monzó, J., Quispe-Fuentes, I., Puente,
 448 L., & Di Scala, K. (2015). Influence of drying temperature on dietary fibre, rehydration
 449 properties, texture and microstructure of cape gooseberry (physalis peruviana l.). *Journal of*
 450 *Food Science and Technology*, 52, 2304-2311.

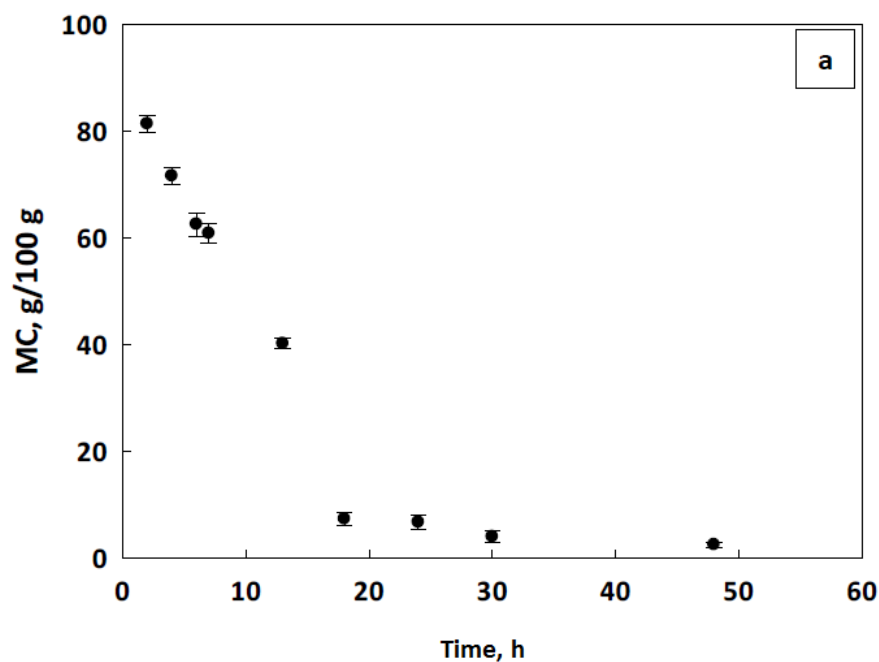
451 Yadav, A. K., & Singh, S. V. (2014). Osmotic dehydration of fruits and vegetables: a review. *Journal of*
 452 *Food Science and Technology*, 51, 1654-1673.

453



455

456 **Fig. 1:** Moisture content (MC) evolution during oven drying at 50 °C. Each value is expressed
457 as mean \pm SD (n=3), statistical significance was assessed by one-way ANOVA.



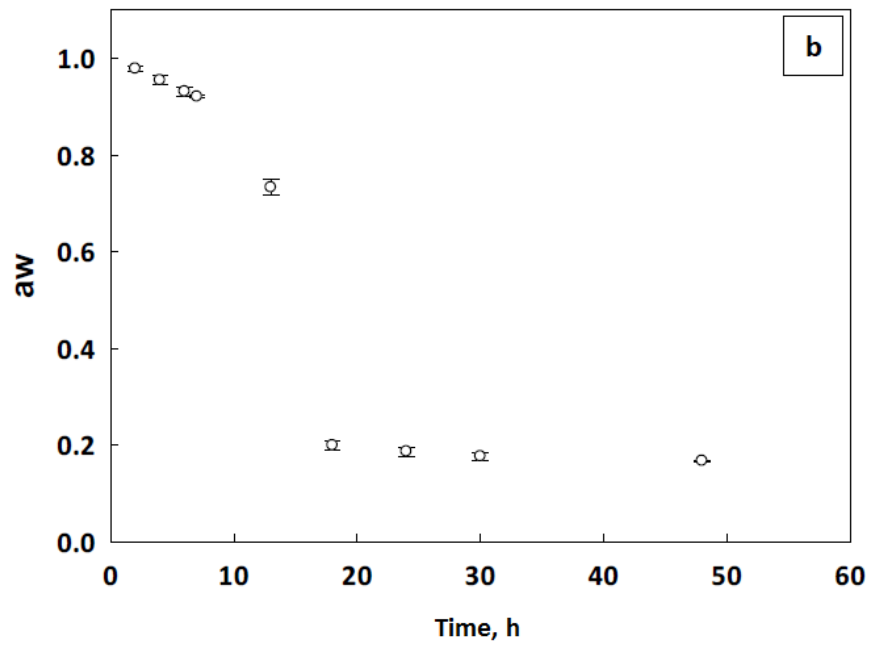


Fig. 2: Evolution over the time of: (a) Moisture content (MC); (b) Water activity (a_w).

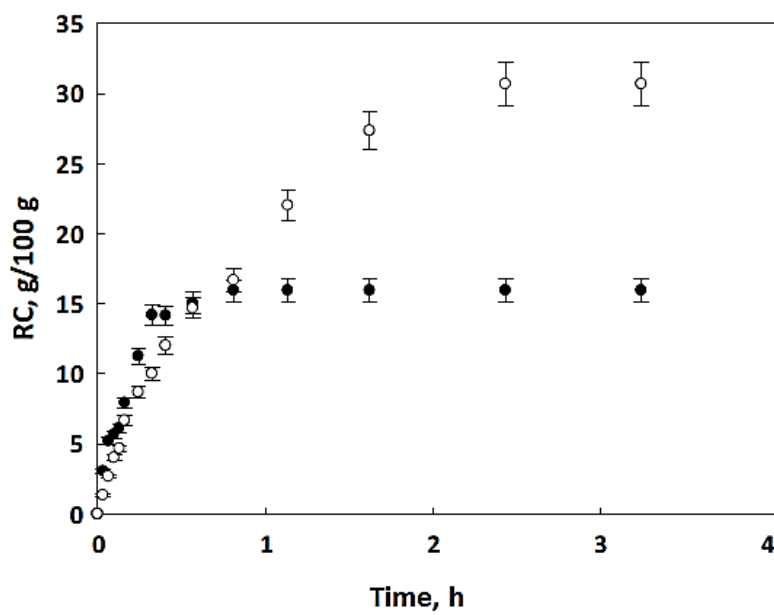


Fig. 3: Comparison between the rehydration behaviour of oven dried and osmotic dehydration + oven dried samples: ● oven drying; ○ osmotic dehydration +oven drying; RC: rehydration capacity.

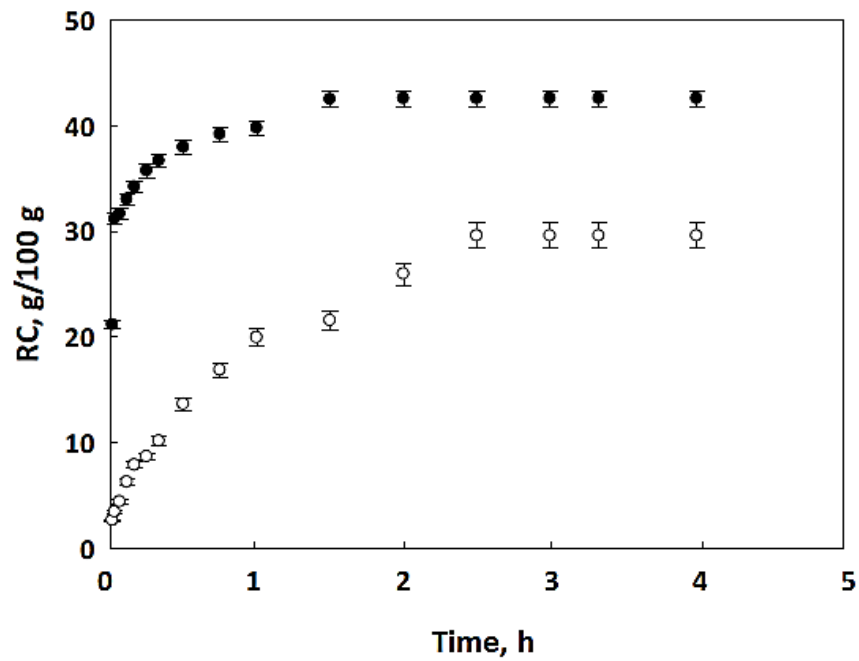


Fig. 4: Comparison between the rehydration behaviour of freeze dried and osmotic dehydration + freeze dried samples: ● freeze drying; ○ osmotic dehydration +freeze drying; RC: rehydration capacity.

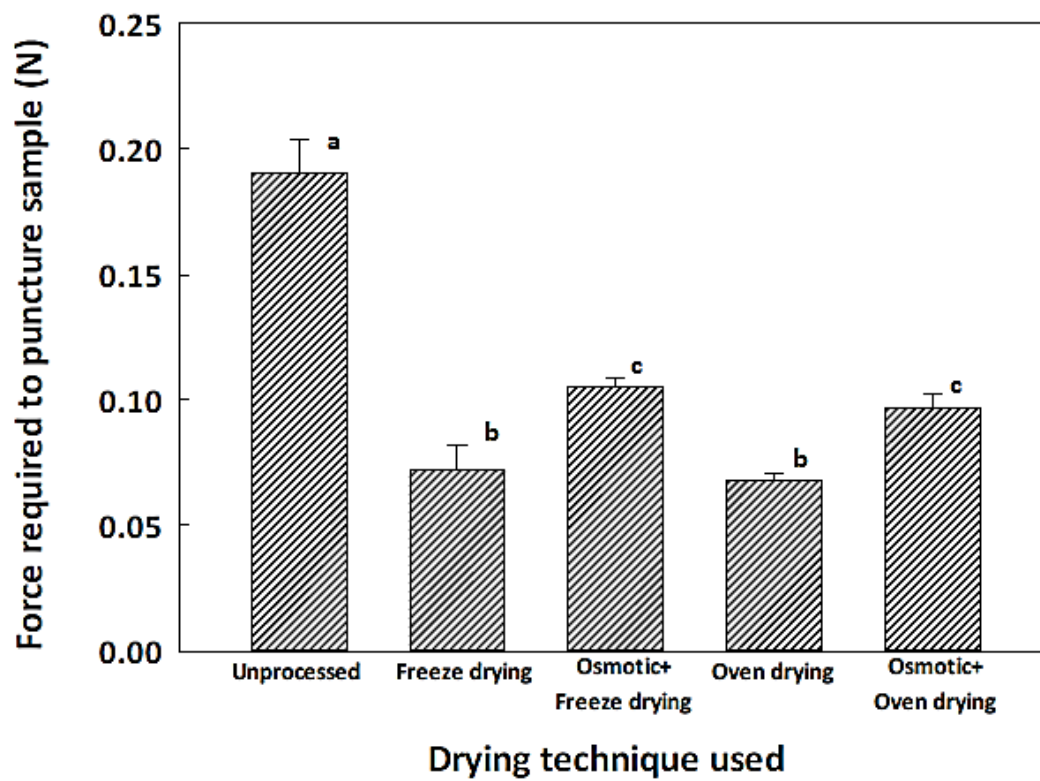


Fig. 5: Puncture penetration testing of strawberries dried using different techniques and rehydrated at room temperature. Each value is expressed as mean \pm SD (n=3). The values followed by the same letter (abc) are not significantly different according to one-way ANOVA and Tukey's multiple comparison tests.

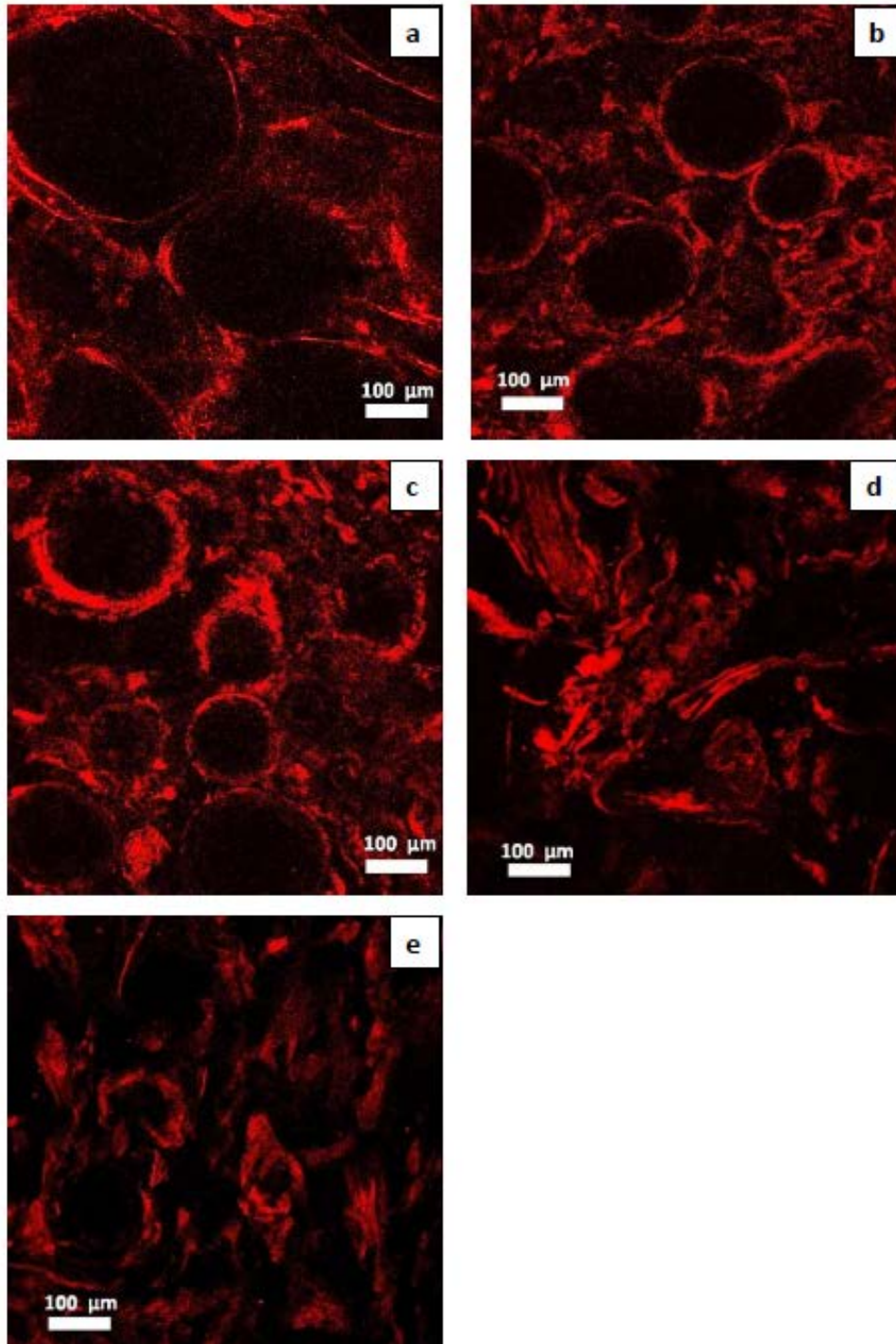


Fig. 6: Confocal microscope images of strawberry cortex cells: (a) unprocessed sample; (b) freeze dried sample; (c) osmotic+freeze dried sample; (d) oven dried sample; (e) osmotic+oven dried sample.

Table 1: Summary of the osmotic dehydration experiments. Each value is expressed as mean \pm SD (n=3). The values followed by the same letter (abcdefghi) in the columns are not significantly different according to one-way ANOVA and Tukey's multiple comparison tests.

#	Osmotic agent	C [°Bx]	T [°C]	t [h]	MC [g/100 g]	a_w	SG % [°Bx]
1	Maltodextrin	40	25	3	75.91 \pm 0.82 ^a	0.985 \pm 0.003 ^a	1.03 \pm 0.03 ^a
2	Sucrose	40	25	3	70.53 \pm 1.90 ^b	0.957 \pm 0.006 ^b	1.78 \pm 0.04 ^b
3	Maltose	40	25	3	71.70 \pm 1.40 ^b	0.960 \pm 0.004 ^{b,c}	1.75 \pm 0.05 ^b
4	Fructose	40	25	3	58.90 \pm 1.46 ^c	0.951 \pm 0.003 ^{b,c}	2.15 \pm 0.06 ^c
5	Fructose	20	25	3	76.70 \pm 1.15 ^a	0.974 \pm 0.006 ^{a,c}	1.97 \pm 0.02 ^d
6	Fructose	60	25	3	44.60 \pm 1.45 ^d	0.910 \pm 0.003 ^d	3.20 \pm 0.03 ^e
7	Fructose	60	35	3	31.84 \pm 0.92 ^e	0.780 \pm 0.005 ^e	3.47 \pm 0.03 ^f
8	Fructose	60	50	3	18.77 \pm 1.06 ^f	0.705 \pm 0.003 ^f	4.22 \pm 0.02 ^g
9	Fructose	60	50	1	67.83 \pm 1.25 ^b	0.966 \pm 0.009 ^{b,c}	1.69 \pm 0.05 ^h
10	Fructose	60	50	5	18.10 \pm 1.13 ^f	0.695 \pm 0.007 ^f	4.34 \pm 0.04 ⁱ

C: concentration of the osmotic solution; T: temperature; t: processing time; MC: moisture content; a_w : water activity; SG: solid gain

Table 2: Osmotic agents' molecular weight.

Osmotic agent	Molecular weight [g/mol]
Maltodextrin	957.5
Sucrose	342.3
Maltose	342.3
Fructose	180.2

Table 3: Oven drying and osmotic dehydration+oven drying experiments. Each value is expressed as mean \pm SD (n=3). The values followed by the same letter (abcd) in the columns are not significantly different according to one-way ANOVA and Tukey's multiple comparison tests.

#	Process	T [°C]	MC [g/100 g]	a_w
1	Oven drying	40	80.1 \pm 2.06 ^a	0.978 \pm 0.008 ^a
2	Oven drying	50	75.6 \pm 1.51 ^b	0.966 \pm 0.008 ^{a,b}
3	Oven drying	60	66.4 \pm 1.75 ^c	0.958 \pm 0.005 ^b
4	Osmotic+oven drying	50	6.7 \pm 0.47 ^d	0.437 \pm 0.004 ^c

T: temperature; MC: moisture content; a_w : water activity

Table 4: Freeze drying and osmotic dehydration+freeze drying experiments. Each value is expressed as mean \pm SD (n=3) .The values followed by the same letter (abc) in the columns are not significantly different according to one-way ANOVA and Tukey's multiple comparison tests.

#	Process	Time [h]	MC [g/100 g]	a_w
1	Freeze drying	7	61.04 \pm 1.11 ^a	0.920 \pm 0.007 ^a
2	Freeze drying	18	7.38 \pm 0.80 ^b	0.195 \pm 0.007 ^b
3	Osmotic+Freeze drying	(3)+4	15.34 \pm 0.96 ^c	0.461 \pm 0.003 ^c
4	Osmotic+Freeze drying	(3)+7	7.52 \pm 0.79 ^b	0.195 \pm 0.006 ^b

MC: moisture content; a_w : water activity